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A Statistical Study of the Variation of Temperature in the Troposphere and Lower Stratosphere

by

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SUMMARY

Correlation coefficients are evaluated between temperatures at 500 mb and at three levels in the lower stratosphere (highest 60 mb) and, respectively, the pressure at the tropopause and the height of the 300 mb level, for Larkhill, Lerwick, Arctic Bay and Malta for the four mid-season months. The Dines type of relationship is confirmed for those regions and seasons affected by travelling depressions and anticyclones. Interesting seasonal changes in the stratospheric coefficients are noted at Lerwick, caused in part by the influence of the cold Arctic winter stratosphere and possibly also related to ozone amounts. Figures for the persistence of upper air temperatures are derived in the course of the analysis.

1. Introduction

In temperate latitudes there is a well known relationship between upper air temperatures and the general pressure distribution and level of the tropopause respectively. A cold troposphere is associated with low pressure in the upper troposphere and a low height of the tropopause, the stratosphere being correspondingly warm; a warm troposphere occurs with high pressure in the upper troposphere, a high level of the tropopause and a cold stratosphere above it. The relationship is partly demonstrated by the correlation coefficients of Dines[1] and is described in many textbooks.

Bannon[2] has discussed the above model of upper air characteristics in connection with a classification of upper air temperature according to the pressure of the tropopause. Sawyer[3] has also discussed the relative effects of advection and vertical motion in causing changes in the height of the tropopause, coming to the conclusion that they are of equal importance, other factors such as dissipation and re-formation being much less important.

Dines'[1] correlation coefficients give quantitative evidence of the general model for the troposphere and his discussion gives qualitative evidence for the lower stratosphere. Ballon-sonde observations from a number of stations throughout Europe were all used together in the evaluation of the coefficients. The approximate magnitudes of these coefficients have been confirmed by Priestley[4] for southern England. Corresponding correlation coefficients have not been evaluated for the lower stratosphere.

It has been pointed out by several writers (for example, Riehl[5]) that this model of upper air temperature variation does not always describe the temperatures at high latitudes where the stratosphere may be relatively cold above a troposphere

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which is also cold for its locality. It is known also that over the Antarctic in winter, temperature sometimes decreases with height up to all levels so far explored by radio-sonde and there is no stratosphere. (See, for example, Schumacher(6)). Upper air temperatures in the tropics have little variation and there is little evidence that there is much systematic variation with pressure distribution or tropopause level.

There is thus a need for quantitative test of the model of upper air temperature variation for two reasons, viz:

(i) to find for what range of latitudes the model is applicable to the atmosphere and the relative merits of the model for different latitudes and seasons.

(ii) to find how far into the stratosphere the model is applicable.

The answer to (ii) will supply, among other things, indirect information as to how high into the stratosphere the effects of the disturbances of the troposphere (depressions and anticyclones, etc.) are noticeable.

Accordingly, a series of correlation coefficients has been evaluated for four stations; Arctic Bay (73°N 85°18'W), Lerwick (60°8'N 1°11'W), Larkhill (51°11'N 1°48'W), and Malta (35°50'N 14°27'E). Observations from Aden (12°50'N 45°1'E) and a number of Pacific stations within 20° Lat. of the Equator have also been scrutinised. The correlation coefficients are between the height of the 300 mb level (H_{300}) and temperatures at the 500 mb level (T_{500}) and at three levels in the stratosphere; also between pressure at the tropopause (P_T) and temperature at the same levels as above. For Arctic Bay the height of the 400 mb level was substituted for the height of the 300 mb level as the tropopause is often below the 300 mb level at that station. These pairs of variables were suggested, of course, by the correlations of Dines between pressure at 9 Km. (P_9) and mean temperature 1-9 Km. (T_9) (correlation coefficient = 0.95), between P_9 and height of the tropopause H_c (0.84), between H_c and T_9 (0.79). Priestley(4) has shown that T_{500} is a good approximation to the mean temperature of the troposphere for this statistical purpose. The height of the 300 mb level is approximately equivalent to the pressure at 9 Km. and the pressure of the tropopause was used as a measure of its height.

2. Data

Statistics were evaluated for the four months January, April, July and October. The data used were as follows:

(i) Larkhill

Observations made four times daily (03, 09, 15, 21 h G.M.T. approximately) in the period 1948-1950 inclusive.

Statistics between H_{300} and T_{500}, H_{300} and P_T, and P_T and T_{500} were prepared from the 03h and 15h G.M.T. observations only, as the relation between these measures is well established and unlike observations at 100 and 60 mb few observations were missing from the records.

(ii) Lerwick

Observations four times daily in the period 1948-1950 inclusive.

(iii) Arctic Bay

Observations made at 03h and 15h G.M.T. daily in the period 1948-1950 inclusive. In January soundings frequently did not penetrate far into the stratosphere; for this month observations for the period 1947-1951 were used.

/iv Malta

(iv) Malta

Observations at 03h and 15h G.M.T. daily for the period 1948-1951 inclusive.

(v) Aden and tropical Pacific stations

Correlation coefficients were not attempted but observations were scrutinised for three years (1949-51) at Aden and for certain months in 1949, 1950 and 1951 for the Pacific stations.

The data for Larkhill, Lerwick, Malta and Aden are tabulated in the Upper Air Climatological Branch. Data for Arctic Bay are recorded in the Meteorological Office Library on microfilm supplied by the Canadian Meteorological Service. The observations for the Pacific islands are available in the Daily Series Synoptic Weather Maps published by the U.S. Weather Bureau.

The pressure of the tropopause is tabulated for all the observations analysed except those for the Pacific Islands; for these the tropopause was determined from the standard level readings and the temperatures recorded at "special points" when these were given. Current Meteorological Office definitions (see, for example, the Introduction to the Daily Aerological Record) could be applied without difficulty to these tropical tropopauses which are usually simple in structure.*

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* Selecting the level of the tropopause at British or Arctic stations is usually straightforward.

At Malta, however, two tropopauses are commonly evident, except in summer when usually a high tropical tropopause is found at a pressure just less than 100 mb. Except in summer only the lower tropopause was normally tabulated in the period analysed; unless stated otherwise the statistics refer to this lower tropopause. The definitions used in the determination of tropopause were not sufficiently precise when the tropopause was "double" to ensure uniformity of practice and to this extent the statistics for Malta may be in error.

To assess this error the tropopauses for Malta were redetermined for the 1950,1951 data using the experimental definitions for the tropopause described in M.O.555 Part 3 (Upper Air Data: Habbaniya). The greatest number of changes in tropopause level required in any month was 28 (October 1950), but the number of changes in other months was much less, usually under 10. The effect of these changes on the statistics was not great; thus the greatest change in the mean pressure at the tropopause for a particular month was 13 mb (January 1950) and the changes in correlation coefficients between P_T and T_{500} and between P_T and T_{100} evaluated for the mid-season months of 1950, 1951 separately were no greater than was to be expected from the size of the samples worked. The largest change was from 0.42 corrected to 0.66 for October, 1950, from 48 observations having some coherence so that the number of independent observations was of the order of ten. It is concluded that the statistics for Malta for the whole period 1948-1951 are not significantly in error.

3. Results

The main statistical results of the investigation are given in Tables I, II, III and IV for Larkhill, Lerwick, Arctic Bay and Malta respectively. The statistics are given for each mid-season month separately. Thus in Table I the second column gives values of ρ , the correlation coefficient between the height of the 300 mb level (H_{300}) and the temperatures at 500 mb (T_{500}), 150 mb (T_{150}), 100 mb (T_{100}), 60 mb (T_{60}) and the pressure at the tropopause (P_T) respectively. The third column gives the mean of the values of H_{300} used in the calculation of ρ , the fourth column gives the standard deviation (σ_H) of these values of H_{300}, the fifth and sixth columns give the mean ($\overline{T}$) and the standard deviation (σ_T) respectively of the temperatures (T_{500}, T_{150} etc.) which were correlated with H_{300}; the seventh column gives the numbers of observations used in the calculations. The other columns are similarly defined.

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Regarding the numbers of observations used in the statistics it must be remembered that temperature observations at a fixed level above one station will show some persistence from one observation to the next. Carruthers[7] quotes a "persistence length" of three days for daily temperature readings at a fixed hour in a conventional screen near the earth's surface. Lewis and McIntosh[8] find 5 as the "equivalent number of repetitions" for the departures of the Edinburgh daily mean temperature for 1950 from the corresponding 50-year average. Craddock[9] however found little correlation between the 6-hour thickness tendency at Larkhill in the layers 1,000-700 mb and 700-500 mb and the similar tendencies after 24 hours or more.

It was necessary therefore to discover the amount of coherence (or persistence) in a series of upper air temperatures and accordingly Lewis and McIntosh's[8] procedure was applied to T_{500} and T_{150} for Lerwick for January and July, 1950, for Malta for January and July, 1951; also to T_{500} for January, 1948 and July, 1950 and to T_{200} for July, 1949, for Arctic Bay. There were insufficient observations at 200 mb at Arctic Bay in any January to make an estimate of persistence. The results are given in Table V, the persistence being calculated from the Formula (2) of that paper for the "equivalent number of repetitions".

Table V

Persistence (in hours) of upper air temperature

	January		July	
	500 mb.	150 mb.	500 mb.	150 mb.
Lerwick (1950)	36 Q	40 Q	48 A	27 Q
Malta (1951)	66 A	42 A	60 A	72 A
Arctic Bay	500 mb.	200 mb.	500 mb.	200 mb.
	66 (1948) A	-	66(1950) A	60(1949) Q

A = s.d. of temperature near average

Q = " " " more than 1°F. less than average.

The figures can only give a rough estimate of the persistence as presumably this will depend to some extent on the character of the weather in the particular month chosen for scrutiny. The variability of temperature in those particular months is some indication of their character and the letters A (average) and Q (quiet) are used for this purpose in the Table, A signifying that the standard deviation of temperature is roughly the same, and Q that it is more than 1°F. less than the appropriate long-term standard deviation.

It was thought that persistence should be greater in quiet settled weather. Accordingly the persistence was estimated for T_{500} for Larkhill for the period 12th-31st August, 1947, when the weather was mainly anticyclonic and fine over southern England. Surprisingly the persistence was less than 24 hours, the standard deviation of temperature being about half that of the long-term value.

It would seem that the number of independent observations in the Lerwick and Larkhill data is about 45-50 (dividing the total number by seven or eight if a persistence of nearly two days is assumed and there are four observations per day). For Malta and Arctic Bay the number of independent observations is only 30-40. For T_{100} and T_{60} where the numbers of observations are much reduced, the series of observations will have less coherence than a full series; it is impossible to estimate the correct number of observations without investigating where observations are missing in the series, but assuming a fair measure of

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scatter of the observations throughout the period, the number of independent observations may be assumed to be 30-35 at 60 mb and 35-40 at 100 mb at Larkhill and Lerwick, but rather fewer at Malta. In the same way the number of independent observations at 150 mb at Arctic Bay (Table III) may be estimated as 20-25 in January and 30 in July.

Casual errors or the regular diurnal variation of the temperatures may be expected to reduce the correlation coefficients. The reduction will only be appreciable, however, when these errors or the diurnal variations are such that the scale of the ratio of their standard deviation to the standard deviation of temperature is comparable with unity. For Larkhill(10), Lerwick(11) and Malta(12) diurnal variation of temperature about the mean at 100 mb (the highest level for which there are reliable data for the last two), is less than 3°F.; assuming the standard deviation of the diurnal variation to be about 3°F., its ratio to the standard deviation of temperature (all observations) is at most 0.4 and thus negligible. For lower levels the ratio is smaller. Casual instrumental errors of the British type radiosonde have a standard deviation of 2°F. in the stratosphere and considerably less in the troposphere(13) so that their effect on the correlation coefficients will be even less than that of the diurnal variation. At 60 mb the diurnal variation at Larkhill is about 4.7°F. in July and the corresponding standard deviation of temperature is 6.5°F. so that the standard deviation of the diurnal variation is of the same order as the standard deviation of temperature when "corrected" for diurnal variation. The correlation coefficients for T_{60} might therefore be reduced in the ratio $1/\sqrt{2}$ from what might be called the "true" values. For other months the reduction would be much smaller. It may be assumed that there may be a similar error in the coefficients for T_{60} for Lerwick and Malta.

Diurnal variation of temperature in the upper air at Arctic Bay would be expected to be small, since observations are made at about 21 and 09h local time (03 and 15 G.M.T.). This was found to be the case. Differences between monthly mean-temperatures at 150 mb for the two hours for January, April, July, October for the years investigated being at most 2.7°F. and showing the 03 G.M.T. means less than the 15 G.M.T. means in January and April but the reverse in July and October, indicating no systematic diurnal variation. Radiation effects would be expected to be most noticeable in April and October when there is a proper night and day at Arctic Bay. For other levels below 150 mb, except near the ground, diurnal variation of temperature should also be small. Casual observational errors of the U.S.A. type radio-sonde used at Arctic Bay are not known but may be assumed to be of the same order of magnitude as the errors of the British radio-sonde.

As a check that diurnal variation has little effect on the correlation coefficients in Tables I - IV, the coefficients for P_T against T_{500} and T_{100} for Lerwick and Malta, all seasons, and for P_T against T_{500} and T_{200} for Arctic Bay, April and October only, were evaluated for the hours 03 and 15 G.M.T. separately. The results show no significant variation from the values given in Tables I - IV, the largest difference being 0.42 - 0.27 (Malta, P_T, T_{100} for April) which is not significantly large considering the numbers of observations.

Statistics are not presented for Aden or for the Pacific stations. It was obvious that no significant correlation could be discovered from the data. For the Pacific stations the range of temperature at each of the levels 500, 300 and 200 mb for a particular month is about 10°C., variations from day to day usually being considerably less (2-3°C.). Such variations are probably not much greater than the observational errors to be expected. It may be that some relation will be found between upper air temperatures and, for example, the tropopause pressure in the Tropics for the organized disturbances, easterly waves, etc. which occur. Data from the tropical Pacific for the regions of the tropopause are only now becoming available in quantity and an analysis of the upper troposphere and lower stratosphere for such occasions may discover some correlations analogous to those for temperate latitudes. It is clear that there is little of the kind to be discovered in undisturbed weather in the troposphere. Aden, however, is not subject to such disturbances and the upper air over it appears to be comparatively steady in character from day to day. There is a little evidence that temperatures

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in the lower stratosphere in the tropics are more variable than in the upper troposphere and it may be that even in undisturbed weather (i.e. undisturbed in the lower stratosphere) some relation may be found between tropopause and stratosphere temperatures. The greater range of stratospheric temperatures may of course be merely the result of their greater liability to error. Observations in the lower stratosphere are as yet too few for a proper analysis.

4. Discussion

(a) Larkhill

The correlation coefficients in Table I, Larkhill, confirm the findings of Dines (1) and Priestley (4) for the troposphere. Table VI below shows corresponding values.

Table VI

Correlation Coefficients Compared

Dines (Europe)	H_c	T_m	0.79	H_c	P_9	0.84	T_m P_9 0.95
Priestley (Larkhill 1944)	H_c	t_{500}	0.79				
Larkhill (1948-1950)	P_T	T_{500}	-0.75	P_T	H_{300}	-0.79	T_{500} H_{300} 0.90

Where H_c = Height of the tropopause

T_m = mean temperature from 1-9 km.

P_9 = the pressure at 9 km.

t_{500} = the departure of temperature at 500 mb from the long period monthly mean

and other symbols have the meanings described in section 3.

The figures for Larkhill are the means of corresponding figures for the 4 months January, April, July, October separately.

Dines' statement that low tropopause is, in general, associated with warm, and high tropopause with cold lower stratosphere is also confirmed by the correlations. P_T was very seldom less than 150 mb so that T_{150} may be considered a stratospheric level.

The stratospheric coefficients are seen to be lowest in April when those for T_{60} are so small as to have little or no significance. These same coefficients are largest in October and January; reference is made to these facts when discussing the Lerwick coefficients.

The decrease of the coefficients with height in the stratosphere is discussed below.

(b) Lerwick

The tropospheric coefficients (Table II) again confirm Dines' well-known results. The stratospheric coefficients are noticeably less in January and April than corresponding values for Larkhill and as this tendency is general among all the stratospheric coefficients it is almost certainly real. The effect is most noticeable at 100 and 60 mb.

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For most of the year the mean temperature in the lower stratosphere increases northwards over the northern hemisphere. In winter, however, the Arctic stratosphere is relatively cold so that the mean temperature distribution in January, at 150 mb for example, shows low temperature over the pole, a belt of higher temperatures in middle latitudes (axis about 55°N. over Britain) and cold again over the tropics. (Authority, unpublished charts in M.O.23). Deviations from the mean distribution occur, of course, so that on some occasions Lerwick may be in or to the south of the warm stratospheric belt and on others, following an excursion of Arctic air southward, it will be within, or on the edge of the Arctic cold stratosphere. This is well illustrated by the winds over Lerwick which on some occasions decrease with height in the stratosphere and on others increase with height when on the edge of the cold Arctic stratosphere (15). The temperature often decreases slowly with height in the stratosphere over Lerwick in winter as has been remarked by Miles (16), though on other occasions the normal increase with height is noted. Riehl(5) has shown that over Arctic Canada in winter the lower stratosphere may be colder or warmer than that to the south although the general weather pattern at the surface is similar.

This variability in the type of temperature distribution in the lower stratosphere in winter is most likely the cause of the low stratospheric coefficients in Table II in January. The explanation of the low stratospheric coefficients for April is more difficult. In April the mean temperatures in the lower stratosphere are higher over the Arctic than in low latitudes though the differences are not so marked as in summer and in autumn. A few occasions are observed in April of wind increasing with height above the tropopause at Lerwick indicating lower stratospheric temperatures to northward, but the number is so small that it is impossible to make the same deductions as for January. Certainly at this period of the year the Arctic stratosphere is warming up quickly or has just become warm rapidly. From the analogy of almost all other atmospheric processes it may be argued that such warming will not be at all uniform in time or space and that the reduced stratospheric coefficients in Table II for April are thus explained. That the reduction in the coefficients is most marked at 60 and 100 mb is explained if the warming of the Arctic stratosphere is affected by absorption of solar radiation in the ozone layer. It is well known that the amount of ozone in the upper atmosphere is greatest over the Arctic in spring and shows a rapid rise in high latitudes between January and March (see, for example, Normand(17)). The greater variability of stratospheric temperature at Lerwick in January and April is shown by the values of standard deviation of temperature at the various levels in Table II.

The stratospheric correlation coefficients in Table II are greatest in October when the amount of ozone in the stratosphere is near its minimum. The Larkhill coefficients are least in April and greatest in October and January and these facts lend further support to the tentative argument in the last paragraph.

(c) Arctic Bay

The correlation coefficients for Arctic Bay(Table III) are of a different character from those for Larkhill and Lerwick. Roughly, in July and to a less extent in October, the coefficients are similar to those for the British Isles. In January and April, however, though P_T and stratospheric temperatures are related in much the same way as at Lerwick and Larkhill, H_{400} a measure of the pressure at the top of the troposphere, or alternatively of tropospheric mean temperature and surface pressure combined, is little related to temperatures in the lower stratosphere. The relation between H_{400} and P_T is, in general, less than the corresponding relation between H_{300} and P_T for Lerwick and Larkhill except in July.

In temperate latitudes the day to day changes of temperature are largely caused by advection and vertical motion. Thus, for example, a rise in temperature at Larkhill at 150 mb may be caused partly by the advection of warmer air and partly by the subsidence of air in the lower stratosphere; the latter is usually associated with a lowering of the tropopause also partly advective and partly caused by subsidence. These advective and subsidal processes show up through the correlation coefficients of Tables I and II discussed above for it is well-known that warm air carries with it a high tropopause and cold air a low tropopause and

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it is also recognised that the air in the extreme upper troposphere and the lower stratosphere subsides over depressions and rises over anticyclones(8). These relations have been discussed in more detail elsewhere (19, 3, 2).

At Arctic Bay in winter and spring there is seldom, if ever, a sequence of weather systems with changing air masses; shallow depressions and feeble anticyclones alternate at the surface. The upper air (500 mb) in these months is dominated by a low which is usually west of Greenland and southeast of Arctic Bay but which oscillates about this position and can have secondary lows associated with it. In summer, and also to a less extent in autumn, frontal depressions affect Arctic Bay but much less frequently than they do the British Isles; the main polar front disturbances are much further to the south. The uniform radiative properties of the vast area of snow or ice in the Arctic, especially in winter and spring, are probably responsible for this uniformity of air mass. It is not surprising, therefore, that the model of upper air temperature relations which applies to western Europe does not apply so well to the Arctic, north of Canada.

Reasonable deductions from the correlation coefficients of Table III are:-

(i) that temperatures in the lower stratosphere are influenced by vertical motion to the same extent as over the British Isles, or perhaps to a slightly greater extent (P_T and T_{250}, T_{200}, T_{150}).

(ii) subsidence at the level of the tropopause is associated with pressure near the top of the troposphere (H_{400}, P_T correlation). The association is not strong but is probably similar to that over the British Isles for the following reasons. Over Britain, advection plays some part in the association of H_{300} and P_T; Sawyer(2) estimates it as similar in magnitude to the effect of vertical motion. The correlation between H_{300} and subsidence at tropopause level would thus be approximately $1/\sqrt{2}$ times the H_{300}, P_T correlation, i.e. about 0.5 or 0.6. Over Arctic Bay advection is probably much less important except in July; the H_{400} P_T correlations of about 0.6 in January, April, and October probably arise through the effect of subsidence, the July coefficient (0.81) being partly caused by advection as well.

(d) Malta

The coefficients in Table IV show another type of relation. In January and April the correlation coefficients are generally similar to those for Lerwick and Larkhill throughout the year; in July and October they are much smaller with the exception of those for T_{500}, H_{300} which merely reflect the static relation between pressure and temperature and the fact that T_{500} varies closely as the mean temperature of the troposphere up to the 300 mb level.

In winter and spring the Central Mediterranean is affected by travelling disturbances common to temperate latitudes. The correlations in Table IV reflect this-being only a little less than for Larkhill for the same months. In summer, however, Malta's weather is influenced by the sub-tropical high pressure belt, the tropopause is high (about 100 mb) and the temperate latitude correlations are not found. In October the summer weather is breaking and lower tropopauses are found again on many days (12); there is some correlation between P_T and stratospheric temperatures but little relation between the other variables.

As stated previously the tropopause is often double at Malta and as a general rule the lower tropopause was selected for the present analysis. In January and April there is a low level tropopause (i.e. roughly in the range 150 - 300 mb) on almost every occasion; on perhaps one third of occasions there is an upper tropopause (60-120 mb) as well. The analysis took no account of these upper tropopauses so that the correlations involving T_{150} and T_{100} are not entirely representative of true stratospheric conditions as up to one third

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of the observations at these two levels were below the upper tropopause. In July a lower tropopause occurs on a few days and usually there is a single high tropopause. In October a few days occur with a single high tropopause; on others there may be a single low tropopause or a double tropopause. If two tropopauses were reported the lower was accepted for the present analysis so that in the October data there is a mixture of a few high level (tropical) with the predominating low level (temperate) tropopauses. This, however, does not fully explain the low correlations between P_T and tropospheric parameters in October; the correlations between P_T and T_{500} and P_T and T_{100} were evaluated for the years 1950, 1951 separately using only those occasions in October when a low tropopause (i.e. P_T greater than or equal to 150 mb) was found. The results are given in Table X. It is seen that though the relation between P_T and T_{500} was appreciable in 1950, in 1951 it was no more than the value given in Table IV. The stratospheric relation remains substantially unchanged.

(e) Variation of the correlations with height in the stratosphere

It is seen from Tables I - IV that the strength of the relation between temperature in the lower stratosphere and P_T and H_{300}, respectively, decreases with height. (The figures for July in Table IV, Malta are not applicable as the tropopause is usually above the 100 mb level). This decrease in the correlation coefficient with height is probably partly caused by the increasing diurnal variation of temperature at the greater heights (see Section 3) but the consistent decreasing tendency is almost certainly real. Thus, for example, at Larkhill in April (Table I) the coefficients between H_{300} and T_{60} and P_T and T_{60} are so small as to have no significance. Table VII gives the square of the ratio of the coefficients for T_{60} to T_{150} for Larkhill, Lerwick and Malta and for T_{150} to T_{250} for Arctic Bay as an indication of the reduction with height in the relation between stratospheric temperatures and H_{300} and P_T respectively. When the coefficients were not significant at the 5% level (ρ less than 0.34 approximately for the number of independent observations at 60 mb; see, for example, Fisher[14]), the ratios have been omitted.

Table VII

Square of ratios of correlation coefficients at greater and lesser heights in the stratosphere

	Jan. Stratospheric temperature &		Apr. Stratospheric temperature &		July Stratospheric temperature &		Oct. Stratospheric temperature &		Mean Stratospheric temperature &	
	H_{300}	P_T	H_{300}	P_T	H_{300}	P_T	H_{300}	P_T	H_{300}	P_T
Larkhill	.62	.30	-	-	.34	.21	.45	.48	.47	.33
Lerwick	-	-	-	-	.25	.28	.49	.45	.37	.37
Malta	.28	.30 (above for 60 mb and 150 mb)	-	-	-	-	-	-	-	-
Arctic Bay	-	.59 (for 150 mb and 250 mb)	-	.73	.80	.74	-	-	-	.69

The means of these ratios shown in the last two columns are almost certainly underestimates of the mean decrease with height of the relation between stratospheric temperatures and H_{300} and P_T respectively since small values of ρ, neglected as insignificant, occurred mainly at 60 mb. The general deduction is therefore that the relations between temperature in the lower stratosphere and H_{300} and P_T respectively are reduced by a factor of more than 2 between 150 and 60 mb at Larkhill, Lerwick and Malta. At Arctic Bay the relation between P_T and T_{250} is not much greater than the relation between P_T and T_{150}.

5. Variation from year to year

Over the British Isles and in many other areas also, the character of the weather in a particular month varies markedly from year to year. It was thought that such variations might have a bearing on the meaning of the correlation

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coefficients set out in Tables I - IV, and accordingly correlation coefficients for a selection of parameters were evaluated for each year separately. Table VIII shows the various statistics for P_T against T_{500} and P_T against T_{100} for Lerwick, Table IX, the statistics for P_T against T_{500} and T_{200} for Arctic Bay and Table X the statistics for P_T against T_{500} and T_{100} for Malta.

(a) Lerwick

The figures for January, 1948 are interesting. In that month there were many instances of wind increasing with height in the stratosphere indicating a cold stratosphere to northward. The coefficient for P_T, T_{100} is so small that there can have been little relation between these two variables and that for P_T and T_{500} is much smaller than for 1949 and 1950. Compare the argument in Section 5 (b). The annual variations in the other coefficients do not appear significant; such variations might be expected from samples of these small sizes from one general population.

(b) Arctic Bay

Here again with the exception of the figures for October, 1949, the coefficients show no significant variation. In October, 1949, upper air temperatures over Arctic Bay varied little; weather was anticyclonic and "quiet" and the standard deviations of T_{500} and T_{200} were smaller than usual. It may be presumed that the temperature variations were so small that other factors, e.g. non adiabatic processes or errors of observation, were of comparable magnitude, thus explaining the lack of correlation.

(c) Malta

The P_T, T_{500} coefficients show little significant variation. The more marked variation in the coefficients for P_T, T_{100} may well be real; the behaviour of the upper atmosphere appears to vary from year to year. Thus, in April, 1951 an upper tropopause was in evidence on 27 soundings while in 1950 it occurred on more than 50 of the 60 soundings.

6. Conclusions

This statistical investigation has confirmed for the British Isles the relations between upper air temperatures and the level of the tropopause and the pressure in the upper troposphere respectively, which Dines deduced quantitatively for the troposphere and qualitatively for the lower stratosphere from observations made over Europe. At Arctic Bay, however, relations of the Dines type do not occur in winter and spring though they do in summer when frontal depressions affect the area and to a limited extent in autumn also. On the other hand at Malta such relations only hold in winter and spring when temperate latitude weather systems affect the Mediterranean and not at all in summer when stable sub-tropical weather prevails; in autumn though the weather is reverting towards the type of more temperate latitudes, the relations are still weak. There appear to be no relations of the Dines type in the tropics, though the observations in the lower stratosphere are insufficient to show this with certainty.

A reasonable generalisation from these results, and one which is not surprising, is that the Dines type of model for atmospheric temperatures holds only in those regions affected by the travelling depressions and anticyclones usually associated with temperate latitudes.

The seasonal variation of the correlation coefficients at Lerwick are interesting. The low correlations in January probably arise from excursions of Arctic air southwards with a cold stratosphere. The low stratospheric correlations in April, and high correlations in October are thought to be associated with ozone amounts in the high atmosphere. Further work is necessary on both these peculiarities.

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A rapid decrease of the correlation coefficients with height in the lower stratosphere has been found except at Arctic Bay where observations are not available in any number at high altitudes. This was expected. The numerical values obtained indicate that the influence at the 60 mb level of the travelling depressions and anticyclones of middle latitudes is less than 0.5 that at 150 mb.

The variation of the correlation coefficients from year to year was small in general. This has little meaning when the coefficients are small but for the larger coefficients, shows the generality of the Dines model of temperature relation.

The correlation analysis used in this investigation can only test for a linear relation between the variables. A more refined analysis could be made without difficulty which would show up non-linear relations between pairs of variables if observations were grouped by mechanical sorting into ranges of tropopause pressure and height of the 300 mb level respectively.

The peculiarities of the cold Arctic stratosphere and possible relations between stratospheric temperatures and ozone amounts can probably best be studied by synoptic methods in the first place.

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TABLE I.

Statistics for Larkhill 1948-1950

	H_{300}					P_T					
	ρ	$\bar{H}_{300}$ (10's of ft.)	σ_H (10's of ft.)	$\bar{T}$ (°F, -ve)	σ_T (°F.)	No. of Obs.	ρ	$\bar{P}_T$ (mb)	σ_{P_T} (mb)	$\bar{T}$ (°F, -ve)	σ_T (°F.)	No. of Obs.
			JANUARY							JANUARY		
T_{500}	+.86	2970	77	10	8.6	177	-.79	237	52	10	8.5	175
T_{150}	-.79	2971	76	69	10.4	322	+.77	234	52	69	10.7	321
T_{100}	-.73	2982	73	73	8.4	253	+.67	227	47	73	8.5	252
T_{60}	-.62	2999	66	75	8.4	69	+.42	217	49	75	8.2	68
P_T	-.81	2971	77			175						
			APRIL							APRIL		
T_{500}	+.91	2980	67	9	9.6	174	-.84	257	61	9	9.4	169
T_{150}	-.75	2983	66	62	8.6	309	+.75	252	57	62	8.6	307
T_{100}	-.57	2984	66	65	7.3	260	+.55	252	56	65	7.3	259
T_{60}	-.26	3008	54	64	7.0	74	+.22	244	59	64	7.0	74
P_T	-.89	2978	67			169						
			JULY							JULY		
T_{500}	+.91	3082	44	+6	6.0	183	-.64	226	34	+6	6.0	182
T_{150}	-.74	3082	44	60	7.7	355	+.70	223	33	60	7.7	354
T_{100}	-.65	3083	44	61	6.6	308	+.51	222	33	61	6.6	307
T_{60}	-.43	3099	41	58	6.3	88	+.32	216	31	58	6.3	87
P_T	-.67	3082	44			182						
			OCTOBER							OCTOBER		
T_{500}	+.91	3040	66	+1	9.3	183	-.72	220	51	+1	9.3	181
T_{150}	-.82	3041	66	73	9.4	354	+.78	217	51	73	9.3	352
T_{100}	-.74	3040	64	73	7.4	310	+.65	217	49	73	7.4	308
T_{60}	-.55	3044	60	71	6.4	105	+.54	217	51	71	6.4	105
P_T	-.80	3040	67			181						

H_{300} = height of 300 mb surface

P_T = pressure at tropopause

T_{500}, T_{150} etc. = temperature (°F.) at 500, 150 mb etc.

ρ = appropriate correlation coefficient σ_H = standard deviation of H_{300}

σ_{P_T} = standard deviation of P_T σ_T = standard deviation of T

/TABLE II.

TABLE II

Statistics for Lerwick 1948-1950

	H_{300}						P_T					
	ρ	$\bar{H}_{300}$	σ_H	$\bar{T}$	σ_T	No.of Obs.	ρ	$\bar{P}_T$	σ_{P_T}	$\bar{T}$	σ_T	No.of Obs.
		(10's of ft.)	(10's of ft.)	(°F,-ve)	(°F.)			(mb)	(mb)	(°F,-ve)	(°F.)	
			JANUARY							JANUARY		
T_{500}	+.85	2895	75	18	10.3	361	-.78	265	61	18	10.3	356
T_{150}	-.53	2897	75	68	9.6	315	+.69	261	62	68	9.6	315
T_{100}	-.27	2900	77	70	7.7	245	+.42	266	62	70	7.7	245
T_{60}	-.07	2922	73	73	7.3	43	+.05	255	61	73	7.3	43
P_T	-.76	2896	75			356						
			APRIL							APRIL		
T_{500}	+.86	2912	65	16	9.0	351	-.72	291	60	16	8.9	343
T_{150}	-.46	2910	64	54	8.9	310	+.64	291	60	56	8.9	309
T_{100}	-.21	2908	62	57	7.6	237	+.42	291	59	57	7.6	236
T_{60}	-.17	2926	61	55	7.7	40	+.18	286	63	55	7.7	40
P_T	-.74	2911	65			341						
			JULY							JULY		
T_{500}	+.91	3033	51	+1	7.1	367	-.82	245	35	+1	7.0	358
T150	-.81	3032	51	51	7.2	338	+.75	245	35	51	7.2	336
T_{100}	-.67	3032	51	51	5.3	298	+.56	245	36	51	5.3	296
T_{60}	-.41	3046	60	49	5.5	97	+.40	237	38	49	5.5	96
P_T	-.81	3029	51			358						
			OCTOBER							OCTOBER		
T_{500}	+.86	2967	71	8	11.0	367	-.74	247	57	8	11.1	362
T_{150}	-.83	2967	71	63	9.4	343	+.78	247	57	63	9.4	343
T_{100}	-.75	2965	72	64	7.1	292	+.70	248	58	64	7.1	293
T_{60}	-.58	2966	67	65	6.6	79	+.52	243	56	65	6.6	79
P_T	-.82	2966	71			362						

For explanation of symbols see Table I.

/TABLE III

TABLE III

Statistics for Arctic Bay 1948-1950

	H_{400}					P_T					
	ρ	$-H_{400}$ (10's of ft.)	σ_H (10's of ft.)	$-T$ (°F,-ve)	σ_T (°F.)	No. of Obs.	ρ	$-P_T$ (mb)	σ_{P_T} (mb)	$-T$ (°F,-ve)	σ_T (°F.)	No. of Obs.
		JANUARY (1947-1951)						JANUARY (1947-1951)				
T_{500}	+.88	2123	35	45	8.1	260	-.53	298	44	45	7.8	191
T_{250}	-.39	2126	40	73	11.0	164	+.73	294	45	76	11.7	155
T_{200}	-.36	2129	40	71	11.1	96	+.75	302	49	71	11.1	96
T_{150}	-.10	2136	39	71	11.1	44	+.56	297	52	71	11.1	44
P_T	-.54	2121	38			191						
		APRIL						APRIL				
T_{500}	+.87	2175	57	40	9.3	174	-.63	327	47	40	9.2	161
T_{250}	-.27	2175	57	62	12.6	150	+.68	326	48	62	12.6	150
T_{200}	-.25	2175	59	55	11.3	129	+.63	327	50	55	11.3	129
T_{150}	-.28	2178	58	52	9.1	113	+.58	327	49	52	9.1	113
P_T	-.67	2175	56			161						
		JULY						JULY				
T_{500}	+.84	2332	41	9	7.4	180	-.81	272	44	9	7.5	165
T_{250}	-.77	2337	41	56	10.6	166	+.77	271	44	56	10.7	164
T_{200}	-.78	2333	41	49	9.4	164	+.77	271	44	49	9.4	162
T_{150}	-.69	2332	41	46	6.2	153	+.66	272	44	46	6.2	151
P_T	-.81	2332	42			165						
		OCTOBER						OCTOBER				
T_{500}	+.65	2184	36	32	7.7	132	-.63	310	38	33	7.9	93
T_{250}	-.56	2185	36	60	8.7	108	+.64	309	37	58	8.2	88
T_{200}	-.44	2184	34	56	6.5	90	+.54	310	36	55	5.9	75
T_{150}	-.25	2187	33	57	5.3	68	+.41	305	35	53	5.4	56
P_T	-.55	2183	36			93						

H_{400} = height of 400 mb surface

Other symbols as on Table I except
σ_H = standard deviation of H_{400}

/TABLE IV

TABLE IV

Statistics for Malta 1948-1951

	H_{300}					P_T					
	ρ	$\bar{H}_{300}$	σ_H	$\bar{T}$	σ_T	No. of Obs.	ρ	$\bar{P}$	σ_{P_T}	$\bar{T}$	σ_T	No. of Obs.
		(10's of ft.)	(10's of ft.)	(°F,-ve)	(°F.)			(mb)	(mb)	(°F,-ve)	(°F.)	
			JANUARY						JANUARY			
T_{500}	+.87	3009	42	6	6.3	197	-.69	235	46	6	6.3	197
T_{150}	-.64	3007	42	68	7.6	189	+.68	234	45	68	7.6	189
T_{100}	-.55	3011	41	75	5.9	162	+.47	233	45	75	5.9	162
T_{60}	-.34	3021	37	78	6.1	58	+.37	222	47	78	6.1	58
P_T	-.72	3005	42			196						
			APRIL						APRIL			
T_{500}	+.90	3052	38	0	5.9	182	-.73	216	39	0	6.0	175
T_{150}	-.61	3052	40	69	7.6	171	+.71	215	39	69	7.6	170
T_{100}	-.41	3051	37	74	5.5	142	+.42	215	38	74	5.5	142
T_{60}	-.11	3054	38	72	5.5	43	+.19	218	41	72	5.5	43
P_T	-.78	3051	39			175						
			JULY						JULY			
T_{500}	+.69	3167	23	+18	4.0	191	-.18	99	19	+19	4.2	142
T_{150}		3167	23	72	4.8	182	-.36	99	19	72	4.5	142
T_{100}	-.27	3167	23	85	5.0	171	+.11	98	19	85	4.8	141
T_{60}	-.30	3172	22	79	7.4	97	+.34	96	19	80	7.2	87
P_T	-.16	3169	21			142						
			OCTOBER						OCTOBER			
T_{500}	+.79	3096	31	+7	4.8	216	-.45	182	31	+7	4.4	203
T_{150}	-.38	3096	31	76	6.1	206	+.62	181	32	76	6.8	202
T_{100}	-.27	3100	31	78	6.3	178	+.38	180	30	78	6.3	177
T_{60}	-.07	3108	26	76	6.3	79	-.12	179	21	76	6.3	79
P_T	-.35	3096	31			204						

For explanation of symbols see Table I.

/TABLE VIII

TABLE VIII

Variation of Statistics from Year to Year

Lerwick 1948-1950

	P_T T_{500}						P_T T_{100}					
Year	ρ	$\bar{P}_T$	σ_{P_T}	$\bar{T}_{500}$	σ_T	No. of Obs.	ρ	$\bar{P}_T$	σ_{P_T}	$\bar{T}_{100}$	σ_T	No. of Obs.
	(-ve)	(mb)	(mb)	(^oF,-ve)	(^oF.)			(mb)	(mb)	(^oF,-ve)	(^oF.)	
		JANUARY							JANUARY			
1948	0.45	291	40	25	7.3	114	0.24	297	44	69	8.6	69
1949	0.86	251	78	17	11.6	122	0.61	259	79	74	8.7	78
1950	0.78	253	50	14	7.4	120	0.42	250	47	68	4.3	98
		APRIL							APRIL			
1948	0.73	287	59	15	9.3	111	0.47	287	60	55	5.2	57
1949	0.60	270	54	14	9.1	116	0.32	268	51	61	9.4	83
1950	0.79	317	59	19	7.3	116	0.43	315	55	56	5.6	96
		JULY							JULY			
1948	0.81	245	37	0	7.2	116	0.61	244	36	52	6.1	93
1949	0.83	234	35	+4	6.6	119	0.51	233	36	52	5.3	100
1950	0.77	257	29	2	5.8	123	0.41	258	31	48	3.1	103
		OCTOBER							OCTOBER			
1948	0.72	255	54	10	11.2	122	0.63	255	52	64	6.7	101
1949	0.76	236	59	6	10.6	118	0.79	236	60	65	7.4	99
1950	0.73	251	57	8	9.2	122	0.68	253	60	64	7.1	93

For explanation of symbols see Table I.

/TABLE IX

TABLE IX

Variation of Statistics from Year to Year

Arctic Bay 1948-1950

Year	P_T T_{500} ρ	$\bar{P}_T$	σ_{P_T}	$\bar{T}_{500}$	σ_T	No. of Obs.	P_T T_{200} ρ	$\bar{P}_T$	σ_{P_T}	$\bar{T}_{200}$	σ_T	No. of Obs.
	(-ve)	(mb)	(mb)	(°F,-ve)	(°F.)			(mb)	(mb)	(°F,-ve)	(°F.)	
		JANUARY (1947-1951)						JANUARY (1947-1951)				
1947	0.67	275	29	39	5.9	39	0.61	278	29	79	7.1	12
1948	0.50	320	45	44	8.3	40	0.55	331	52	64	10.3	22
1949	0.67	279	30	48	7.2	37	0.50					5
1950	0.84	324	40	49	6.9	26	0.89	316	40	72	7.8	13
1951	0.45	300	46	44	6.6	49	0.78	297	46	71	10.7	44
		APRIL						APRIL				
1948	0.65	303	35	38	10.2	51	0.47	297	36	63	8.1	36
1949	0.66	326	39	42	7.0	56	0.58	327	41	58	9.7	45
1950	0.76	350	53	39	9.8	54	0.71	350	55	45	5.6	48
		JULY						JULY				
1948	0.76	251	37	6	6.7	57	0.70	251	38	54	9.1	56
1949	0.67	278	36	11	6.4	59	0.67	277	36	48	6.1	58
1950	0.90	288	50	11	8.3	49	0.84	288	51	43	8.9	48
		OCTOBER						OCTOBER				
1948	0.59	296	28	31	6.0	24	0.57	302	22	57	7.0	21
1949	0.18	301	23	29	3.2	24	0.13	302	23	59	4.6	20
1950	0.66	322	45	34	10.0	45	0.64	321	45	53	5.4	34

For explanation of symbols see Table I.

/TABLE X

TABLE X

Variation of Statistics from Year to Year

Malta 1948-1951

Year	P_T T_{500} ρ	$\bar{P}_T$ (mb)	σ_{P_T} (mb)	$\bar{T}_{500}$ (°F,-ve)	σ_T (°F.)	No. of Obs.	P_T T_{100} ρ	$\bar{P}_T$ (mb)	σ_{P_T} (mb)	$\bar{T}_{100}$ (°F,-ve)	σ_T (°F.)	No. of Obs.
	(-ve)											
		JANUARY						JANUARY				
1948	0.62	223	45	3	7.0	47	0.54	220	44	75	5.6	38
1949	0.71	245	49	5	5.9	34	0.28	236	46	73	5.1	22
1950	0.70	224	40	8	5.5	50	0.27	223	42	76	5.1	46
1951	0.72	239	40	7	5.9	62	0.65	238	40	75	6.6	56
		APRIL						APRIL				
1948	0.78	221	44	+1	4.7	26	0.53	224	48	69	4.1	20
1949	0.61	208	28	+2	5.5	44	0.14	205	26	76	5.1	38
1950	0.85	239	46	2	6.7	47	0.21	236	29	72	5.1	38
1951	0.72	207	26	0	5.6	56	0.44	208	26	75	4.2	44
		JULY						JULY				
1948	+0.13	112	24	+20	3.3	12						
1949	0.18	117	18	+18	4.8	30						
1950	0.22	093	14	+20	3.5	47						
1951	0.09	101	11	+17	3.5	54						
		OCTOBER						OCTOBER				
1948	0.34	182	27	+9	4.4	46	0.29	178	24	80	7.2	38
1949	0.45	200	29	+5	3.1	50	0.43	197	28	77	4.7	45
1950	0.66	177	31	+9	4.9	48	0.42	178	31	78	7.1	43
1951	0.36	181	27	+6	4.1	50	0.40	178	23	78	5.7	41

For explanation of symbols see Table I.